Stellar and Galactic Evolution as Informational Tunneling (q→τ)

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Stars and galaxies do not merely assemble—they learn. From turbulent molecular clouds to the grand design spirals of disk galaxies, structure formation can be read as a progressive alignment of the realized state q (matter, fields, feedback) with the latent generative structure τ (conservation laws, boundary conditions, symmetries, and environment). We frame stellar and galactic evolution as Informational Tunneling: a constrained gradient flow that monotonically reduces the divergence $D(q \parallel \tau)$ while radiative and dynamical processes export entropy and radiate coherence. In this view, the main sequence is a manifold of $q \approx \tau$ attractors; stellar feedback acts as a control loop that keeps interstellar media near viable operating points; and the baryon cycle of galaxies—accretion, star formation, winds, fountains, AGN—implements a multi-scale alignment protocol that transforms chaotic inflows into predictable scaling relations. Dark components (halos, cosmological expansion) provide informational curvature: missing columns of τ that close dynamical budgets without overfitting local data. We show how star formation laws, initial mass functions, metallicity gradients, and galaxy quenching can be recast as stationarity conditions for a generalized entropy functional, and we derive falsifiable consequences: self-regulation slopes, burst–quench duty cycles, and stability boundaries, each interpreted as minima of $D(q \parallel \tau)$ under realistic constraints.

Keywords: stellar evolution, galactic evolution, informational tunneling, alignment dynamics, feedback regulation, baryon cycle, star formation law, initial mass function, metallicity gradients, quenching, Active Galactic Nucleus (AGN) feedback, turbulence, entropy, complexity.

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1. Premise: Alignment as Astrophysics

1.1 q (state) vs. τ (constraints) for stars and galaxies

- Objects.
    - q: the realized, time-dependent state of a system—fields and budgets resolved at the scale of interest. For baryons this includes $\rho(\mathrm{x}, t)$, v, P, temperature T, metal mass fractions Z_i, ionization states, magnetic field B, radiation field I_ν, phase fractions (molecular/atomic/ionized), and subgrid closures (e.g., turbulence, feedback deposition kernels).
    - τ: the generative structure—constraints, symmetries, boundary conditions, and constitutive maps that make the data. Concretely: conservation of mass, momentum, energy and metals; Maxwell + MHD; gravity (Poisson or cosmological background); radiative transfer; equation of state; transport laws (conduction, viscosity, diffusion); stability criteria (e.g., Toomre Q); boundary fluxes (cosmic inflow, tidal fields); and controller-like feedback laws (stellar/AGN yields, coupling efficiencies).
- Stars (micro→meso).
  τencodes hydrostatic balance, energy generation, and transport:

$$\frac{dP}{dr} = -\frac{Gm(r)\rho}{r^2}, \frac{dm}{dr} = 4\pi r^2 \rho, \frac{dL}{dr} = 4\pi r^2 \rho\, \varepsilon, \frac{dT}{dr} = \frac{T}{P}\nabla\frac{dP}{dr},$$

with microphysics $\varepsilon(\rho, T, X)$, opacity $\kappa(\rho, T, Z)$, and convection criteria. The realized q is a stellar model (profiles P, T, ρ, L) plus composition Xthat *satisfies* these simultaneously.

- Galaxies (meso→macro).
  τ provides budget and stability constraints under a halo potential Φ:
  mass: $\partial_t \rho + \nabla \cdot (\rho \mathrm{v}) = S_\rho$(inflow, sinks),
  momentum: $\partial_t(\rho \mathrm{v}) + \nabla \cdot (\rho \mathrm{vv} + P\mathbb{I} + \mathbb{M}) = -\rho\nabla\Phi + \mathrm{S}_p$,
  energy: $\partial_t e + \nabla \cdot [(e + P)\mathrm{v} + \mathrm{F}_{\mathrm{rad}}] = \Gamma - \Lambda + S_e$,
  metals: $\partial_t(\rho Z) + \nabla \cdot (\rho Z \mathrm{v} - \mathrm{J}_Z) = y\,\dot{\rho}_\star - \mathcal{L}_Z$.
  Disk stability (e.g., Toomre $Q \approx \frac{\kappa\sigma}{\pi G\Sigma} \gtrsim 1$), angular-momentum transport, and boundary fluxes through the CGM complete τ. The realized $q$is the multiphase ISM+CGM+stellar distribution and kinematics that close these budgets.
- Interpretation. “Alignment” means $q$evolves toward satisfying the τ set with minimal slack: hydrostatic/virial balance, regulated star formation, and feedback that keeps

budgets consistent—observable as stable main-sequence stars and self-regulated galaxies.

1.2 Divergence $D(q \parallel \tau)$ as coarse-grained loss; radiance as alignment

- What D measures. A nonnegative functional that quantifies mismatch between the realized state and the generative constraints after coarse-graining to accessible observables $\mathcal{O}$:

$$D(q \parallel \tau) \equiv \mathrm{KL}(p_q(\mathcal{O}) \parallel p_\tau(\mathcal{O}))\text{or}D = \int w_i \frac{[\mathcal{C}_i(q) - \mathcal{C}_i(\tau)]^2}{\sigma_i^2}\, dV,$$

where $\mathcal{C}_i$ are constraint residuals (e.g., net heating–cooling, virial error, metal budget imbalance), σ_i are tolerances set by transport/feedback, and p_τ is the maximum-entropy distribution consistent with τ. In quantum/line-of-sight contexts (e.g., nebular lines) D can be a relative entropy between predicted and observed spectra or moment maps.

- Alignment flow (Informational Tunneling). Dynamics implement a constrained gradient descent:

$$\dot{q} = -\mathcal{G}^{-1}(q)\, \nabla_q D(q \parallel \tau) \text{ subject to conservation and boundary fluxes,}$$

where $\mathcal{G}$ encodes transport (diffusion, turbulence, radiation). The principle is $\dot{D} \leq 0$: each physical update should not increase mismatch after admissible coarse-graining.

- Radiance as the signature of descent. Lowering D typically requires exporting entropy/energy via radiation or winds:
    - Stars: ignition enforces $\Gamma_{\mathrm{nuc}} \approx \Lambda_{\mathrm{rad}}$ at the core; the star radiates coherence—a stable luminosity Lthat reflects $q \approx \tau$.
    - Galaxies: self-regulation sets $\dot{M}_\star \approx \eta^{-1}(\dot{M}_{\mathrm{in}} - \dot{M}_{\mathrm{out}})$ with feedback yield ηadjusting so that disk stability and CGM pressure balance hold. The Kennicutt–Schmidt slope and mass–metallicity relation appear where $\partial D / \partial(\dot{M}_\star) = 0$.
- Diagnostics (practical D-terms).
    - Stars: $D \supset \int [H(\rho, T, X) - C(\rho, T, Z)]^2/\sigma_H^2\, dr$+ convective stability residuals + boundary mismatches at the photosphere.

- Galaxies: $D \supset \int [(\nabla \cdot \mathrm{F}_{\mathrm{energy}}) - (\Gamma - \Lambda)]^2/\sigma_e^2 + (Q-1)^2_-/\sigma_Q^2 + (\dot{Z}_{\mathrm{box}} - y\dot{M}_\star + \cdots)^2/\sigma_Z^2 \, dV$, plus penalties for violating angular-momentum and mass continuity under measured inflow/outflow.

- Phenomenology. As $D \to 0$ at fixed τ:
  - Stars settle onto the main-sequence manifold; secular drift (aging) is slow, controlled by fuel and opacity evolution.
  - Galaxies converge to scaling relations (Tully–Fisher, mass–metallicity, fundamental plane) with scatter tracing residual stochasticity in boundary terms (inflow variance, feedback duty cycles).
- Forecast. If alignment is the grammar, then (i) burst–quench cycles, (ii) IMF environment bounds, and (iii) CGM phase fractions emerge where $\delta D = 0$ under perturbations of the relevant controls—giving clean, testable slopes and variances without ad hoc tuning.

Takeaway: Define q as what is realized, τ as what must be satisfied, and D as the minimal mismatch you can't explain away. Stellar and galactic evolution are then the monotone descent of D under real transport and feedback—coherence shows up as light, winds, and stable laws.

2. Formalism for Baryonic Systems

2.1 Conserved budgets (mass, momentum, energy, metals, angular momentum) as τ

We encode the *generative structure* τas a set of conservation laws, constitutive relations, and boundary terms on a domain Ω (star, ISM+CGM, or galaxy). With q the realized fields, the constraints are:

- Mass (continuity):

$$\partial_t \rho + \nabla \cdot (\rho \mathrm{v}) = S_\rho (\text{inflows, sinks, SF, returns})$$

- Momentum (Euler/MHD):

$$\partial_t (\rho \mathrm{v}) + \nabla \cdot (\rho \mathrm{vv} + P\mathbb{I} + \mathbb{M}) = -\rho \nabla \Phi + \mathrm{S}_p$$

Here $\mathbb{M}$ is magnetic/turbulent stress; Φ is the gravitational potential (halo + baryons).

- Energy (thermal + kinetic + CR/radiative if tracked):

$$\partial_t e + \nabla \cdot [(e+P)\mathrm{v} + \mathrm{F}_{\mathrm{rad}} + \mathrm{F}_{\mathrm{CR}}] = \Gamma - \Lambda + S_e$$

with heating Γ (e.g., feedback), cooling Λ, and transport fluxes $\mathrm{F}_{\mathrm{rad}}, \mathrm{F}_{\mathrm{CR}}$.

- Metals (each species or total Z):

$$\partial_t(\rho Z) + \nabla \cdot (\rho Z\, \mathrm{v} - \mathrm{J}_Z) = y\, \dot{\rho}_\star - \mathcal{L}_Z$$

where $y$is the yield, J_Z diffusive/turbulent mixing.

- Angular momentum (axisymmetric form):

$$\partial_t(\rho \mathrm{l}) + \nabla \cdot (\rho \mathrm{l}\, \mathrm{v} - \mathbb{T}) = \mathrm{S}_l$$

with $\mathrm{l} = \mathrm{r} \times \mathrm{v}$, and $\mathbb{T}$ the torque/viscous–magnetic stress.

- Closure & stability (constitutive maps in τ):

$$P = P(\rho, T, Z, \dots), \kappa = \kappa(\rho, T, Z), \text{Toomre } Q(\Sigma, \sigma, \kappa_{\mathrm{ep}}) \gtrsim 1, \text{ etc.}$$

Boundary conditions provide inflow/outflow, radiation escape, and CGM pressure. These are the *equations q must satisfy*; their residuals define mismatch.

2.2 Gradient-flow dynamics: $\dot{q} = -\mathcal{G}^{-1}\nabla_q D$ under feedback and transport constraints

We take Informational Tunneling as a constrained gradient flow that monotonically reduces a coarse-grained divergence $D(q \parallel \tau)$:

- Divergence functional (schematic):

$$D = \int_\Omega \sum_i w_i \frac{[\mathcal{C}_i(q;\, \tau)]^2}{\sigma_i^2}\, dV,$$

where $\mathcal{C}_i$ are *constraint residuals* (continuity, energy balance, stability, metal budget, etc.), $w_i$weights, σ_i tolerances fixed by transport/feedback.

- Flow with conservation built in:

$$\dot{q} \;=\; -\mathcal{G}^{-1}(q)\, \nabla_q D \text{s.t.} \mathcal{A}(q) = 0$$

$\mathcal{A}$ bundles the *exact* conservation constraints (e.g., integral mass/metal/AM budgets), enforced via Lagrange multipliers. $\mathcal{G}$ is a positive semi-definite metric/Onsager operator encoding transport (diffusion, radiation, mixing) and response times.

- Operator structure (examples):
  - Scalars (e.g., T, Z): $\mathcal{G} \approx \tau_T^{-1} - \nabla \cdot (D_T \nabla \cdot)$.
  - Vectors (e.g., v): $\mathcal{G} \approx \tau_v^{-1}\mathbb{I} - \nabla \cdot (\nu \nabla \cdot)$.
  - Radiative fields: $\mathcal{G}$includes a streaming–diffusion split (M1/FLD).
- Feedback as controllers inside $\mathcal{G}$and $\nabla_q D$:
  Stellar/AGN feedback enters (i) sources Γ, S_p, S_e and (ii) the *gain* of the response: higher mismatch (e.g., over-dense, under-stable gas) increases coupling until residuals shrink—proportional–integral control that guarantees $\dot{D} \leq 0$ under mild conditions (convexity of D, positive $\mathcal{G}$).
- Stationarity (radiative coherence):

  $\nabla_q D = 0$ $\Rightarrow$ steady states with $q \approx \tau$:

for stars: $\Gamma_{\mathrm{nuc}} \approx \Lambda_{\mathrm{rad}}$ and hydrostatic balance;
for galaxies: balanced baryon cycle, $Q \gtrsim 1$, stable scaling relations. Perturbations relax as $d(\delta q)/dt \approx -\mathcal{G}^{-1} H_D \, \delta q$ with Hessian $H_D \succcurlyeq 0$.

2.3 Informational curvature for dark sectors (halo potential, cosmological background)

The dark sector provides non-baryonic structure that shapes feasible baryonic states. In the alignment frame:

- Halo potential as fixed columns of τ:
  Solve $\nabla^2 \Phi_{\mathrm{dm}} = 4\pi G \rho_{\mathrm{dm}}$(e.g., NFW/EIN profiles or simulation-derived). The pair $(\Phi_{\mathrm{dm}}, \partial_t \Phi_{\mathrm{dm}})$define *geometric constraints* that baryons must satisfy. We call these *informational curvature* because they bend the feasible set of $q$without adding baryonic equations.
- Cosmological background as slow, global constraints:
  Expansion $H(t)$, growth rate $f(a)$, and accretion histories set boundary fluxes
  S_ρ, $\mathbf{S}_p$, S_e
  at the halo virial surface. They also set the CGM pressure/entropy floor that enters τ.

- Implementation in D:
  Add residuals penalizing *virial/Jeans mismatch* in the dark potential and *mass–energy closure* with cosmological inflow:

$$D_{\mathrm{grav}} = \int_{\Omega} w_v \frac{[\nabla \cdot (\rho \mathrm{vv} + P\mathbb{I} + \mathbb{M}) + \rho \nabla \Phi]^2}{\sigma_v^2} \, dV,$$
$$D_{\mathrm{bdy}} = \int_{\partial\Omega} w_b \frac{(\mathcal{F}_{\mathrm{obs}} - \mathcal{F}_{\tau})^2}{\sigma_b^2} \, dA,$$

where $\mathcal{F}$ collects inflow/outflow and radiation boundary fluxes.

- Dark energy / large-scale tides:
  Enter as slowly varying background terms in $\Phi$and $\partial_t \Phi$, and as priors on the *target distributions* $p_\tau(\mathcal{O})$used in D (e.g., mass–metallicity, TF, baryon fraction vs. halo mass).

- Operational payoff:
  Treating Φ_{dm} and cosmological inflows as *informational curvature* clarifies why many galactic laws are tight and slowly varying: they are minima of D on a manifold bent by the halo and the background. Deviations (e.g., starburst outliers, quenched satellites) are *geodesic excursions* driven by transient boundary terms, and they relax as $\dot{D} \leq 0$ pulls q back toward the τ-manifold.

Summary: τ is the book of budgets and closures; $q$is the realized, multiphase state; D measures mismatch; $\mathcal{G}$ turns that mismatch into physically allowed updates; and the dark sector supplies *informational curvature* that shapes which aligned states exist.

3. Star Formation as q→τ

3.1 Cloud assembly: turbulence, gravity, magnetic support; coherence via dissipation

- Initial state (q): a supersonic, magnetized, radiatively cooling cloud with density PDF ~ lognormal plus power-law tail at high ρ; virial parameter $\alpha_{\mathrm{vir}} \equiv 2E_{\mathrm{kin}}/| E_{\mathrm{grav}} |$, magnetization via M_A (Alfvén Mach), and sonic Mach $\mathcal{M}$.

- Constraints (τ): momentum/energy budgets in a galactic potential; magnetic flux freezing (imperfect via ambipolar diffusion), radiative transfer, and thermal balance.

- Alignment mechanism: shocks and ion–neutral drift dissipate turbulent power; gravity concentrates mass where the *local* Jeans (or magneto-Jeans) criterion is first met. The

descent of $D(q \parallel \tau)$ is the joint reduction of: (i) virial mismatch $(\alpha_{\mathrm{vir}} - 1)$, (ii) force imbalance $|\nabla P + \nabla \cdot \mathbb{M} + \rho \nabla \Phi|$, and (iii) heating–cooling residuals.

- Predictive scalings:
    - Dense-gas fraction f_{dg} increases with $\mathcal{M}$ and decreases with magnetic support M_A^{-2}.
    - Core mass function inherits turbulent cascade and magnetic intermittency; its peak shifts with cooling curve slope (dust/metallicity).
    - Star formation efficiency per free-fall, ϵ_{ff}, emerges as the *stationary throughput* that balances turbulent/feedback driving and collapse losses.

3.2 Ignition = stationarity: heating = cooling, D minimization over EOS + opacity

- Core to protostar: Collapse proceeds until the heating–cooling residual vanishes at the center:

$$\mathcal{R}_H \equiv \Gamma_{\mathrm{comp}} + \Gamma_{\mathrm{visc}} + \Gamma_{\mathrm{nuc}}(T, \rho, X) - \Lambda_{\mathrm{rad}}(T, \rho, Z, \kappa) \;\rightarrow\; 0.$$

Here $\kappa(\rho, T, Z)$ (opacity) and EOS $P(\rho, T)$ are the control knobs.

- Informational stationarity: ignition is the extremum $\frac{\partial D}{\partial \theta_j} = 0$ for microphysical parameters $\theta_j \in \{X, \kappa\,\mathrm{table}$,convective mixing-length, etc.$\}$ subject to hydrostatic constraints.
- Convection vs radiation: where radiative gradient ∇_{rad} exceeds adiabatic ∇_{ad}, convection turns on to enforce $\dot{D} \leq 0$ by transporting entropy outward; the mixing-length that minimizes D sets the stable luminosity L.
- Outcome: a *coherent* protostar with L and T_{eff} fixed by the minimal mismatch between energy generation and transport. Variations in metallicity and dust simply tilt the D landscape (different opacities ⇒ different stationarity points).

3.3 Main sequence as an attractor manifold; evolutionary drift as slow misalignment repair

- Attractor: the main sequence is the low-dimensional set where hydrostatic balance and steady nuclear burning *jointly* solve τ:

$$\left\{ \frac{dP}{dr} = -\frac{Gm\rho}{r^2},\ \frac{dm}{dr} = 4\pi r^2 \rho,\ \frac{dL}{dr} = 4\pi r^2 \rho \varepsilon,\ \frac{dT}{dr} = \frac{T}{P} \nabla \frac{dP}{dr} \right\}.$$

On this manifold D is near its minimum; deviations decay on thermal or dynamical timescales (relaxation back to $q \approx \tau$).

- Mass–luminosity slope: arises as the tangent of the attractor in the (M, L) coordinates determined by opacity/EOS; scatter reflects small D-residuals (rotation, metallicity, magnetic fields).
- Secular evolution: nuclear consumption slowly deforms τ (composition X changes), producing a *drift* along the manifold (isochrones). Red-giant branching is a bifurcation where a previous stationarity (core H-burning) loses stability and a new one (shell burning + expanded envelope) minimizes Dunder new constraints.

3.4 End states: white dwarfs, neutron stars—boundary attractors set by microphysics

- Degenerate endpoints: When thermal pressure can no longer repair mismatch (fuel exhausted, core contracts), quantum microphysics installs hard constraints in τ: electron or neutron degeneracy pressure.
    - White dwarfs: Equilibrium occurs when the degeneracy EOS $P_e(n_e)$ balances gravity; the Chandrasekhar mass is the edge of feasible q for given composition—an attractor boundary where any attempt to increase M raises D steeply (instability to collapse/ignition).
    - Neutron stars: Strong-interaction EOSs define new τ-columns; the TOV equations yield a mass–radius curve whose stable branch are the finite-radius minima of D.
- Explosive transitions: Type Ia SNe (runaway C/O ignition) or core-collapse SNe occur when the system cannot find a neighboring minimum of D under the old microphysics; a discrete update (burning, neutrino heating) changes τ and lands q on a new attractor (remnant + ejecta).
- Observables as alignment diagnostics:
    - WD and NS mass–radius relations = maps of τ's microphysical constraints; deviations probe EOS columns.
    - Nucleosynthetic yields and light curves quantify how far—and how quickly—D dropped during the transition (how efficiently energy was channeled into coherent radiance vs. turbulent losses).

Takeaway: Star formation is the monotone descent of mismatch from chaotic clouds to stable burners. Turbulence and magnetic fields sculpt the descent; ignition is the stationarity where heating equals cooling; the main sequence is the attractor manifold; and compact remnants are boundary attractors carved by quantum microphysics.

4. Population-Level Consequences

4.1 Initial Mass Function from alignment and feedback-limited fragmentation

- Setup. Turbulent, magnetized clouds produce a lognormal density PDF with a high-ρ power-law tail from self-gravity. Fragmentation proceeds while the cooling time is shorter than the dynamical time, and stalls when feedback (protostellar radiation, outflows) or magnetic support raises the effective Jeans mass.
- Alignment lens. The IMF emerges where the descent of $D(q \parallel \tau)$ balances three residuals: (i) *virial mismatch* (collapse wants to continue), (ii) *thermo-radiative mismatch* (cooling efficiency), and (iii) *feedback mismatch* (local momentum/energy injection).
- Mass scale (turnover). The characteristic mass $m_c$is set by the *stationary* effective Jeans mass at first hydrostatic core formation:

$$m_c \sim \frac{\pi^{5/2}}{6}\,\frac{c_{s,\mathrm{eff}}^3}{G^{3/2}\,\rho_{\mathrm{crit}}^{1/2}}, c_{s,\mathrm{eff}}^2 \equiv c_s^2 + \sigma_{\mathrm{turb}}^2/3 + v_A^2/2 + \Delta c_s^2(\mathrm{rad}),$$

with $\Delta c_s^2\ (\mathrm{rad})$ the radiative-heating contribution from protostars. Stationarity $\frac{\partial D}{\partial m} = 0$ selects m_c where further fragmentation would *increase* D (overcooling/overdensity without support).

- High-mass tail. Competitive accretion and clustered radiation pressure set a feedback-limited growth law $\dot{m} \propto m^{\beta}$with escape probability constraints; the tail slope approaches a Salpeter-like power law when the *feedback residual* becomes scale-free. Alignment predicts a nearly universal high-mass slope with weak environment trends through $c_{s,\mathrm{eff}}$ and accretion geometry.
- Environment dependence (bounded). Metallicity and background radiation shift $\kappa(\rho, T, Z)$ and thus $c_{s,\mathrm{eff}}$, moving m_c. The alignment view predicts modest IMF variation: $m_c \propto \kappa^{\frac{3}{8}}\, n^{-\frac{1}{4}}$ (schematic), with stronger shifts only in extreme $Z \ll Z_{\odot}$ or starburst fields where radiative terms dominate the residual budget.

4.2 Stellar yields and metallicity as descent directions of Din chemo-thermal space

- Chemo-thermal coordinates. Let $q$include $(\rho, T, \{Z_i\})$and τ include enrichment, cooling, and mixing constraints. Define a chemo-thermal divergence

$$D_{\mathrm{CT}} = \int \left[\frac{(\Gamma - \Lambda)^2}{\sigma_e^2} + \sum_i \frac{(\dot{Z}_i - y_i\dot{\rho}_\star + \nabla \cdot \mathrm{J}_{Z_i})^2}{\sigma_{Z,i}^2}\right] dV.$$

- Alignment flow. The gradient flow $\dot{q} = -\mathcal{G}^{-1}\nabla_q D_{\mathrm{CT}}$ pushes gas toward states where (i) heating balances cooling at each phase boundary, and (ii) metal production, removal, and mixing close their budgets. The descent directions are thus:
    - toward cooling sequences that permit star formation where Toomre/Jeans allow;
    - toward yield-consistent metallicities Zthat satisfy box models $d(ZM_{\mathrm{gas}})/dt \approx y\dot{M}_\star - Z\dot{M}_\star - Z\dot{M}_{\mathrm{out}} + \mathrm{mixing}$.
- Observables as gradients.
    - Mass–metallicity relation (MZR): emerges where $\frac{\partial D_{\mathrm{CT}}}{\partial Z} = 0$ given inflow metallicity and mass-loading η: $Z \approx Z_{\mathrm{in}} + \frac{y}{1+\eta+\lambda}$ (schematic λ= dilution/mixing). Scatter corresponds to boundary-term noise (inflow bursts) rather than new parameters.
    - Metallicity gradients: steady negative gradients minimize D_{CT} under inside-out growth and radial transport; bars/flows briefly raise Dthen relax it as mixing terms act.
    - Abundance ratios ($[\alpha/\mathrm{Fe}]$): track *time-delayed* descent with SNIa kernels; $[\alpha/\mathrm{Fe}]$vs. $M_\star$ sequences are *isodescent curves* at fixed star-formation timescale.

4.3 Star-formation law (Σ_{SFR}–Σ_{gas} slopes) as stationarity under transport

- Budget view. On kiloparsec scales, let the residuals include (i) *energy balance* of the ISM, (ii) *vertical momentum* balance against gravity, and (iii) *stability* (Toomre Q). Write

$$D_{\mathrm{sf}} = \int \left[\frac{(\dot{E}_{\mathrm{inj}} - \dot{E}_{\mathrm{diss}})^2}{\sigma_E^2} + \frac{(P_{\mathrm{turb}} + P_{\mathrm{th}} + P_B - W_z)^2}{\sigma_P^2} + \frac{(Q-1)^2}{\sigma_Q^2}\right] dA.$$

Feedback power $\dot{E}_{\mathrm{inj}}$and turbulent pressure P_{turb} scale with Σ_{SFR}.

- Stationarity condition. Minimizing D_{sf} w.r.t. Σ_{SFR}at fixed gas supply and transport coefficients yields

$$\Sigma_{\mathrm{SFR}} \propto \frac{\Sigma_{\mathrm{gas}}}{t_{\mathrm{dep}}(\kappa, \sigma, h, \epsilon_{\mathrm{fb}})},$$

where t_{dep} is the *emergent* depletion time that equalizes injection and dissipation and keeps $Q \approx 1$. If dissipation and vertical support are local, $t_{\mathrm{dep}} \sim \frac{t_{\mathrm{ff}}}{\epsilon_{\mathrm{ff}}}$ gives a super-linear slope in

molecular gas at high $\Sigma_{\rm gas}$; if transport sets the pace (shear, inflow variance), slopes flatten toward linear.

- Slope regimes (predictions).
    - Molecular-dominated discs: $\Sigma_{\rm SFR} \propto \Sigma_{\rm mol}^{N}$ with $N \simeq 1 - 1.5$. $N \to 1$ when feedback self-adjusts $\epsilon_{\rm ff}$ to hold $Q \approx 1$; $N > 1$ in compact starbursts where dissipation becomes density-dependent and winds are less effective at support.
    - Atomic-dominated outskirts: $\Sigma_{\rm SFR}$tracks the *formation* of H $_2$: $N > 1$ transitions to $N \approx 1$ as shielding increases; scatter dominated by UV field and metallicity (parameters in τ).
    - High-z thick discs: elevated $\kappa$and inflow variance shorten $t_{\rm dep}$ mildly, moving systems along the same $D_{\rm sf}$ minimum with higher normalization, not a new law.
- Consistency checks.
    - The same $\Sigma_{\rm SFR}$ that minimizes $D_{\rm sf}$ also minimizes $D_{\rm CT}$ by stabilizing heating–cooling at the phase boundaries.
    - Variations in mass-loading η shift normalization predictably: stronger winds require higher $\Sigma_{\rm SFR}$ to hold $Q \approx 1$ at fixed $\Sigma_{\rm gas}$.
- Falsifiable signatures.
    - At fixed $\Sigma_{\rm gas}$ and shear, increasing feedback coupling lowers D and reduces the slope Ntoward unity.
    - Systems with identical $\Sigma_{\rm gas}$ but higher inflow variance show larger scatter orthogonal to the mean law, as boundary-term noise dominates the residual.

Takeaway: The IMF, chemical scaling relations, and star-formation laws are not separate axioms—they are the population-level fixed points where the descent of Dunder real transport and feedback reaches stationarity. Their slopes, turnovers, and scatters follow from which residuals dominate the budget, yielding clean, testable predictions.

5. Galactic Self-Regulation

5.1 Baryon cycle: accretion → ISM → stars → outflows → CGM

- Budget picture. Let a galaxy be an open control volume with gas mass $M_{\rm g}$. Coarse equations:

$$\dot{M}_{\rm g} = \dot{M}_{\rm in} - (1-R)\,\dot{M}_\star - \dot{M}_{\rm out}, \dot{Z}_{\rm g} M_{\rm g} = y\,\dot{M}_\star + Z_{\rm in}\dot{M}_{\rm in} - Z_{\rm g}[(1-R)\dot{M}_\star + \dot{M}_{\rm out}] - \Phi_Z,$$

where R is the return fraction, y yields, Φ_Z mixing losses to the CGM.

- Cycle as alignment. The system descends $D(q \parallel \tau)$ by routing inflow to star formation and outflow so that continuity, energy, and momentum constraints close with minimal residuals. The steady state ($\dot{M}_{\rm g} \approx 0$) implies

$$\dot{M}_\star \simeq \frac{\dot{M}_{\rm in}}{1-R+\eta}, \eta \equiv \dot{M}_{\rm out}/\dot{M}_\star,$$

i.e., SFR tracks supply once feedback sets η.

- CGM's role. The CGM buffers misalignment: fountain flows and pressure confinement absorb fluctuations, shortening the relaxation time of D after inflow bursts. Phase structure (warm/hot) acts as Lagrange multipliers controlling η and re-accretion.

5.2 Disk stability (Toomre-like) and angular-momentum transport as constraints in τ

- Stability constraint. A star-forming disk must hover near $Q \equiv \frac{\kappa\sigma}{\pi G\Sigma} \approx 1$ (gas+stars generalized). This is a column of τ: violate it and spiral/fragmentation residuals blow up D.

- Vertical momentum balance.

$$P_{\rm turb} + P_{\rm th} + P_B \simeq W_z \equiv \pi G \Sigma_{\rm g} \Sigma_{\rm tot},$$

fixes required turbulent support at given Σ.

- Transport constraint. Radial mass flux $F_R = -2\pi R\,\nu_{\rm eff}\Sigma\left(\frac{\partial \ln \Omega}{\partial \ln R}\right)$ and torque budget (bars/spirals) set the supply of dense gas. In alignment, $\nu_{\rm eff}$ adjusts (via GI-driven turbulence/feedback) so the inflow to the star-forming ring equals the local consumption that minimizes D.

5.3 AGN and stellar feedback as proportional–integral controllers enforcing $\dot{D} \le 0$

- Control law (schematic).

$$\eta = \eta_0 + k_P\,\Delta + k_I \int^t \Delta\, dt', \Delta \equiv (Q-1) \text{ or } [P_{\rm req} - P_{\rm turb}],$$

i.e., mass-loading/coupling ramps with instantaneous and time-integrated misalignment.

- Stellar feedback. SNe, radiation pressure, and winds inject momentum/energy per stellar mass ($p_\star/m_\star, E_\star/m_\star$). In equilibrium, they set $P_{\rm turb}$ to the level that restores $Q \sim 1$, ensuring $\dot{D} \leq 0$ for the disk.
- AGN feedback. When central gas exceeds a BH fueling threshold, AGN power $L_{\rm AGN} \propto \dot{M}_{\rm BH}$ drives jets/winds that raise CGM entropy or expel gas, decreasing cooling inflow and quenching central star formation. The integral term prevents limit cycles by responding to cumulative cooling excess (cluster cool-core alignment).
- Outcome. With positive-definite response (feedback gain) and a convex D, the closed loop is contractive: perturbations in $\Sigma, \sigma, \dot{M}_{\rm in}$ decay on a relaxation time set by transport + feedback.

5.4 Scaling relations (Tully–Fisher, mass–metallicity, fundamental plane) as minima of D

- Tully–Fisher (TF). In a thin, self-regulated disk with $Q \approx 1$ and near-constant baryon fraction $f_{\rm b}$ within the optical radius, minimizing the combined virial and support residuals gives

$$M_{\rm bar} \propto V_{\rm c}^{\alpha}, \alpha \approx 3\text{–}4,$$

where the slope reflects how Σ and σ scale with $V_{\rm c}$ at the D-minimum. Scatter arises from boundary noise (inflow variance, ηfluctuations) rather than new parameters.

- Mass–metallicity relation (MZR). The chemo-thermal minimum of D with steady inflow/outflow yields

$$Z \simeq Z_{\rm in} + \frac{y}{1+\eta+\lambda},$$

with λ summarizing dilution/mixing. Because $\eta(M_\star)$ declines with mass (shallower potentials), Z increases with $M_\star$. The observed secondary dependence on SFR (the "fundamental metallicity relation") is the Lagrange multiplier for the gas-mass constraint at the same D-minimum.

- Fundamental plane (FP) of ellipticals. Minimizing the joint residual in virial equilibrium and entropy/energy budgets for pressure-supported systems gives

$$R_{\rm e} \propto \sigma^{a}\, I_{\rm e}^{b},$$

with a, b shifted from pure virial by stellar population M/L and structural non-homology—both encoded as columns of τ. The FP is the stationary surface where D is minimized given these constraints.

- Other laws as corollaries.
    - SFR–$M_\star$ main sequence: SFR follows $\dot{M}_{\rm in}$ filtered by $(1 - R + \eta)^{-1}$; the slope and scatter reflect the same D-minimum that enforces $Q \approx 1$.
    - Size–mass relations: angular-momentum conservation + torque residuals min → $R \propto \lambda R_{\rm vir}$ with modest scatter tied to spin and feedback history.
    - Gas fractions: at fixed halo mass, $f_{\rm gas}$ sits at the D-minimum balancing depletion time and inflow variance.

Takeaway. A galaxy regulates itself by *closing budgets* with feedback gains tuned by misalignment. Disk stability and transport are the hard constraints in τ; stellar and AGN feedback are the PI controllers that enforce $\dot{D} \leq 0$. The celebrated scaling relations are not separate axioms but the manifolds of minimal D in this closed-loop system, with their slopes and scatters predicted by which residuals dominate.

6. Quenching and Morphological Transformation

6.1 Environmental and internal quenching as bifurcations in the alignment flow

- Dynamical picture. Let the coarse variables be $x \equiv \left(\Sigma_{\rm g}, \sigma, Q, \dot{M}_\star, \eta, Z, M_{\rm BH}, s_{\rm CGM}\right)$ and the control parameters be $u \equiv (\dot{M}_{\rm in}, \Phi_{\rm env}, \epsilon_{\rm fb}^\star, \epsilon_{\rm fb}^{\rm AGN})$. The alignment flow is

$$\dot{x} \;=\; F(x;u) \;=\; -\,\mathcal{G}^{-1}(x)\,\nabla_x D(x;u)\,,$$

with equilibria at $\nabla_x D = 0$. Quenching occurs when an equilibrium with $Q \approx 1$, $\dot{M}_\star > 0$ loses stability as $u$varies—i.e., a bifurcation of the descent dynamics.

- Environmental channels (control via $\Phi_{\rm env}$).
    - Strangulation: $\dot{M}_{\rm in} \downarrow$ (halo shock heating, satellite cut-off) reduces the supply term; the SFR fixed point disappears (saddle-node), $M_{\rm g} \to$ low, $\dot{M}_\star \to 0$.
    - Ram-pressure stripping: explicit sink $S_\rho < 0$at large radii drives $Q > 1$ everywhere; the only minima of D satisfy vertical balance without star-forming gas.

- Harassment/tides: impulsive torques heat the disk ($\sigma \uparrow$), lifting Q; a star-forming minimum persists only if $\dot{M}_{\rm in}$ or feedback-driven cooling can lower Q back to ~ 1.

- Internal channels (control via $\epsilon_{\rm fb}$).
  - AGN maintenance mode: raising CGM entropy $s_{\rm CGM}$ lowers cooling flows, reducing $\dot{M}_{\rm in}$ below the star-forming fixed point's basin—steady, global quench.
  - Starburst exhaustion/compaction (see 6.3): rapid consumption plus outflows transiently empties the central reservoir; if re-supply is slow, the system crosses a separatrix into a quenched minimum (elliptical-like state).

Interpretation: Quenching is not an on/off switch; it is a topological change in the set of D-minimizing states as supply, heating, or stability controls cross critical values.

6.2 Duty cycles and rejuvenation as metastable loops near the τ-manifold edge

- Metastability geometry. Near the edge of feasible alignment (low $\dot{M}_{\rm in}$, high $s_{\rm CGM}$), D develops shallow valleys separated by low barriers: a star-forming minimum (SF) and a quenched minimum (Q). Stochastic boundary fluctuations $\delta\dot{M}_{\rm in}$ and torque noise drive loops SF ↔Q.

- Duty cycle estimator. Model the coarse state as a 1D reaction coordinate y (gas-rich → gas-poor) with effective potential $U(y) \propto D(y)$ and noise $\xi(t)$ from inflow variance:

$$\dot{y} = -\mu\, U'(y) + \sqrt{2D_y}\,\xi(t)\,.$$

Mean residence times obey Kramers-type scaling, $\tau_{\rm SF} \propto \exp\,[\Delta U_{\rm SF}/D_y]$, $\tau_{\rm Q} \propto \exp\,[\Delta U_{\rm Q}/D_y]$. Rejuvenation is frequent when D_y (supply variance) is large and barriers are modest (post-compaction discs, group environments).

- Observables.
  - Green-valley dwell times = $\min\left(\tau_{\rm SF}, \tau_{\rm Q}\right)$ controlled by halo mass (through $s_{\rm CGM}$) and morphology (through σ, bar torques).
  - Spectral fingerprints: upturns in D_n4000 with UV excess; metallicity plateaus during Q because $\frac{\partial D}{\partial Z} \approx 0$ at low $\dot{M}_\star$; re-growth of discs tied to renewed cold inflow.

Interpretation: Duty cycles and rejuvenation are noise-driven traversals between neighboring minima of D near the τ-manifold boundary; the statistics encode the barrier heights set by CGM thermodynamics and angular-momentum supply.

6.3 Bulge growth, bars, and compaction as transient complexity that later reduces D

- Transient complexity principle. Alignment can require temporary growth of structural complexity (central density, non-axisymmetry) so that D can be lowered later under new constraints—mirroring interior-volume growth in black holes before information is radiated.
- Bars as torque engines. A bar introduces a strong $m = 2$ mode, generating torques $\tau_R \sim -\partial\Phi_{m=2}/\partial\phi$, which redistribute angular momentum:

$$\partial_t(\Sigma l_z) + \frac{1}{R}\partial_R(RF_{l_z}) = -\tau_R\,.$$

Gas loses l_z, flows inward, and triggers central star formation/AGN fueling. Initially D can rise (instability energy), but the subsequent central mass concentration establishes a new minimum with stabilized outer disk (higher Q at large R) and efficient feedback control centrally—net drop in D.

- Compaction events. Minor mergers or clump migration drive a blue nugget phase: high $\Sigma_{\rm g}$, short $t_{\rm dep}$, bursty $\dot{M}_\star$. Outflows and consumption then evacuate the core; if CGM heating persists, the system lands on a quenched minimum (red nugget). The compaction is a bridge: a transient, high-complexity state enabling the shift between distinct D-minimizing basins.
- Bulge growth and morphological quenching. A rising central potential increases epicyclic frequency $\kappa$and thus $Q = \kappa\sigma/(\pi G\Sigma)$, pushing the disk toward stability without large σor feedback. The mismatch term $(Q-1)^2_-$in D vanishes at larger Σ than before, extending the stable region of parameter space—fewer local departures from the minimum.
- Predicted signatures.
    - Barred galaxies: enhanced central metallicities at fixed $M_\star$ (fast Z-descent via inflow) with temporarily elevated σ; outer-disc SF suppressed but stabilized.
    - Post-compaction systems: steep age/metallicity gradients, compact bulges, hot CGM; green-valley transits set by barrier heights (6.2).

- Sérsic index vs. depletion time: higher n correlates with longer t_{dep} at fixed Σ_{gas} due to morphological stabilization—movement along a lower-D contour in the $\left(\Sigma_{\mathrm{gas}}, \dot{M}_{\star}\right)$ plane.

Takeaway: Quenching and morphology are features of the alignment landscape. Environment and feedback move the system across bifurcations; noise sculpts duty cycles near the manifold's edge; and non-axisymmetric structures serve as temporary complexity that repositions the galaxy onto lower-D, longer-lived equilibria.

7. Entropy, Complexity, and Radiative Coherence

7.1 Why galaxies "shine to learn": exporting entropy to lower D at fixed constraints

- Thermo-informational identity. For a coarse state q under fixed τ (budgets, boundary fluxes), the divergence $D(q \parallel \tau)$ decomposes into a mismatch of *balance laws* and a *coding* term. Reducing D typically requires *ordering* the baryons (lowering coarse-grained uncertainty) while exporting entropy to the environment. Radiation and winds are the channels:

$$\dot{S}_{\mathrm{tot}} = \dot{S}_{\mathrm{int}} + \dot{S}_{\mathrm{rad}} + \dot{S}_{\mathrm{out}} \geq 0, \dot{D} \propto -\left(\frac{\dot{Q}_{\mathrm{rad}}}{T_{\mathrm{eff}}} + \Pi_{\mathrm{out}}\right) + \mathcal{R}_{\mathrm{resid}},$$

where $\dot{Q}_{\mathrm{rad}}$ is radiated power, T_{eff} a characteristic emission temperature, Π_{out} the entropy exported by outflows, and $\mathcal{R}_{\mathrm{resid}}$ the residual constraint violations. Higher radiative/outflow entropy export → larger negative contribution to $\dot{D}$.

- Physical reading. Gas must *cool* to self-gravitate and fragment; stars must *shine* to maintain hydrostatic structure; galaxies must *radiate and vent* to keep $Q \approx 1$ and close energy/momentum budgets. Hence "galaxies shine to learn": radiative loss is the price for moving q closer to τ.
- Testable corollary. At fixed supply and potential, systems with more efficient radiative channels (higher metallicity/dust ⇒larger Λ) approach the D-minimum faster (shorter depletion time t_{dep}), up to the point where feedback raises T_{eff} or η to maintain stability.

7.2 Complexity growth during assembly; later compression into robust large-scale laws

- Two-phase alignment.

    1. Growth phase (complexity ↑): Mergers, clump migration, bars, and multiphase CGM build structural and dynamical complexity—more components, couplings, and non-axisymmetries. This enlarges the representational capacity of q so constraints in τ (transport, stability, chemo-thermal closure) can be satisfied simultaneously. D falls even as internal complexity $\mathcal{C}$ rises.

    2. Compression phase (simplicity ↑): After assembly, feedback and transport *coarse-grain* the state, pruning degrees of freedom into few-parameter laws (e.g., Tully–Fisher, main sequence, mass–metallicity). Here, D keeps falling while $\mathcal{C}$ declines—a lossy compression that preserves constraint-satisfying behavior.

- Quantitative sketch. Let $\mathcal{C}$ be a proxy (e.g., network description length, number of persistent homology features, or multi-component fit rank). Then

$$\frac{d\mathcal{C}}{dt} \gtrless 0 \text{ while } \frac{dD}{dt} \leq 0,$$

with $\frac{d\mathcal{C}}{dt} > 0$ during violent assembly and $d\mathcal{C}/dt < 0$ during secular settling. The hysteresis $(\mathcal{C}, D)$ loop explains why mature galaxies obey tight relations despite messy formation histories.

- Observational hooks. High-z discs: elevated clumpiness (large $\mathcal{C}$) but already on the star-forming main sequence (low D-residual along SFR–$M_\star$). Low-z spirals/ellipticals: smoother morphologies (smaller $\mathcal{C}$) and even tighter scaling laws (lower D).

7.3 Metallicity gradients and color–magnitude sequences as emergent codes

- Gradients as codes. Radial metallicity profiles $Z(R)$ encode a galaxy's transport and enrichment history. In alignment, $Z(R)$minimizes a chemo-transport part of D:

$$D_Z = \int \frac{[\partial_t(\Sigma Z) + \partial_R(\Sigma Z v_R - \Sigma D_Z\, \partial_R Z) - y\,\Sigma_{\mathrm{SFR}} + \mathcal{S}_Z]^2}{\sigma_Z^2}\, 2\pi R\, dR,$$

whose Euler–Lagrange condition yields steady gradients with inside-out growth and modest diffusion. Bars/inflows imprint temporary inversions, which relax as diffusion and star formation restore the minimal-D profile.

- Color–magnitude sequences (blue/red ridges). Colors summarize SFH and metallicity. The blue sequence is the D-minimum under active supply ($\dot{M}_{\rm in}$ high): SFR tracks inflow, metallicity follows $Z \approx Z_{\rm in} + y/(1+\eta+\lambda)$. The red sequence is the D-minimum when supply is throttled (high CGM entropy or morphological quenching): $\dot{M}_\star \to 0$, colors redden as stellar populations age; metallicity evolves slowly along iso-D contours (passive tracks).
- Predictive patterns.
    - Mass–metallicity–SFR (FMR): arises as a *Lagrange-multiplier sheet* from minimizing D with simultaneous mass and gas constraints—predicting the observed tilt and low orthogonal scatter.
    - Gradient–bar correlation: stronger bars ⇒temporarily flatter or inverted $Z(R)$ and younger central ages; recovery timescale $\tau_{\rm mix} \sim R^2/D_Z$ forecast by the diffusion term in D_Z.
    - Green-valley vectors: motion across the CMD during quenching follows the steepest-descent direction of D: rapid UV fade (SFR drop) at roughly fixed Z, then slow reddening at nearly constant mass.
- Compression to codes. In mature systems, $Z(R)$ and broadband colors function as low-dimensional codes of the high-dimensional baryon cycle. Their tightness (small intrinsic scatter) is the signature that $q$sits near the τ-manifold and that the chemo-thermal part of D is close to minimal.

Takeaway: Galaxies reduce mismatch by radiating and venting entropy, temporarily growing complexity to satisfy constraints, then compressing that complexity into robust empirical codes—metallicity gradients and color–magnitude sequences—that reveal how close $q$lies to τ.

8. Predictions and Tests

8.1 Universal self-regulation slopes tied to accessible control parameters (feedback yield, inflow variance)

- Claim. On kpc scales the star-formation law and depletion time normalize and tilt according to two controls: (i) momentum/energy yield per stellar mass formed $(p_\star/m_\star, E_\star/m_\star)$, and (ii) the variance of cosmological/torque-driven inflow $\sigma_{\rm in}$.
- Scaling at the D-minimum (disk $Q \approx 1$, vertical balance):

$$\Sigma_{\rm SFR} \simeq \frac{\pi G\,\Sigma_{\rm g}\,\Sigma_{\rm tot}}{p_\star/m_\star} \quad \Rightarrow \quad t_{\rm dep} \equiv \frac{\Sigma_{\rm g}}{\Sigma_{\rm SFR}} \propto \frac{p_\star/m_\star}{\Sigma_{\rm tot}}.$$

Prediction: slope $N \equiv \frac{d\ln\Sigma_{\rm SFR}}{d\ln\Sigma_{\rm g}} \approx 1$ when feedback couples efficiently; $N > 1$ (up to ~ 1.5) in compact starbursts where dissipation becomes density-dependent or $(p_\star/m_\star)$ effectively drops.

- Variance imprint: at fixed $\Sigma_{\rm g}$, the orthogonal scatter about the mean law scales as $\sigma_\perp \propto \sigma_{\rm in}/(1+\eta)$.
  Test: Map $\sigma_\perp$ vs. inflow proxies (HI warps, kinematic asymmetries, satellite counts). A tight anti-correlation with $(1+\eta)$ falsifies or supports the control interpretation.

8.2 IMF environment-dependence bounds from stability of the $q \approx \tau$ manifold

- Claim. The main-sequence (stellar) and star-forming (galaxy) attractors remain stable only if the IMF turnover mass $m_c$and high-mass slope vary within bounds that keep feedback and cooling residuals balanced.
- Bound (schematic) from stationarity $\partial D/\,\partial m_c = 0$:

$$\left|\frac{\Delta m_c}{m_c}\right| \lesssim \left|\frac{\Delta\Lambda}{\Lambda}\right|^{3/8} + \left|\frac{\Delta(p_\star/m_\star)}{p_\star/m_\star}\right|^{1/2}.$$

With observed stability of $t_{\rm dep}$ and $Q \approx 1$, expect mild IMF shifts across the star-forming main sequence: $|\,\Delta m_c/m_c\,| \lesssim 0.3$ except in extreme low-Z or nuclear starburst regimes.

- Tests.
  - Compare dynamical M/L and spectral IMF indicators (Na I, CaT) against $t_{\rm dep}$, $\Sigma_{\rm g}$, and Z. A tight M/L–$t_{\rm dep}$ relation with small residuals limits IMF swings.
  - In starbursts, predict coherent tri-variation: (top-heavier IMF) ⇒ lower $p_\star/m_\star$per unit bolometric L⇒ steeper local $\Sigma_{\rm SFR}$–$\Sigma_{\rm g}$ slope and hotter dust. Absence of this tri-variation falsifies large IMF shifts.

8.3 CGM observables (covering fractions, phase structure) as Lagrange multipliers of τ

- Claim. The CGM sets the multipliers that enforce mass/energy closure: pressure floor $P_{\rm CGM}$, entropy $K_{\rm CGM}$, and reaccretion delay $\tau_{\rm reaccr}$. At the D-minimum:

$$\eta \simeq \frac{W_z}{\dot{p}_\star/A} \propto \frac{\Sigma_{\rm g}\Sigma_{\rm tot}}{p_\star/m_\star}, \tau_{\rm reaccr} \propto \frac{K_{\rm CGM}^{3/2}}{\dot{M}_{\rm cool}},$$

implying covering fraction–SFR and entropy–quenching links.

- Predictions.
    - Covering fractions: $f_{\rm cov}$ (cool H I/O VI) anticorrelates with instantaneous η at fixed halo mass, but correlates with time-averaged SFR over ∼Gyr (fountain memory).
    - Phase ratios: OVI/OVII increases with burstiness; quenched systems show elevated $K_{\rm CGM}$, low cool covering, and long $\tau_{\rm reaccr}$.
    - Cluster cores: maintenance-mode AGN raises $K_{\rm CGM}$ to the threshold where $\partial D/\,\partial \dot{M}_{\rm cool} \to 0$; predicts a floor in $\frac{t_{\rm cool}}{t_{\rm ff}}$ near $\sim$ 10–20.
- Tests. Joint CGM–ISM programs (quasar absorption + IFU maps) should find: (i) $f_{\rm cov}$ tracks past SFR on ∼1–2 Gyr lags; (ii) quenched centrals with high $K_{\rm CGM}$ occupy the long-$\tau_{\rm reaccr}$ tail; (iii) satellites show steep drops in cool $f_{\rm cov}$ coincident with ram-pressure signatures, consistent with constraint enforcement at the boundary.

8.4 Burst–quench statistics and green-valley residence times from $\dot{D}$ geometry

- Claim. Near the edge of the τ-manifold, the D landscape has two shallow minima (SF and quenched) separated by a barrier $\Delta U \propto \Delta D$. Stochastic inflow drives transitions; the residence times encode ΔU and the inflow "diffusivity" D_y.
- Predictions.
    - Duty cycles: $\mathrm{DC}_{\rm burst} \equiv t_{\rm burst}/t_{\rm tot} \sim \exp\left(-\Delta U_{\rm burst}/D_y\right)$ decreases with halo mass (higher $K_{\rm CGM}$⇒ larger ΔU).
    - Green-valley times:

$$t_{\rm GV} \approx \frac{\Delta \mathrm{sSFR}}{|\,\dot{\mathrm{sSFR}}\,|} \sim \frac{1}{\lambda_{\rm relax}} \text{with} \lambda_{\rm relax} \sim \mathrm{eig}_{\rm min}(\mathcal{G}^{-1} H_D),$$

implying shorter $t_{\rm GV}$ In systems with strong feedback coupling (larger $\mathcal{G}^{-1}$) and longer $t_{\rm GV}$ where transport is bottlenecked (small $\nu_{\rm eff}$).

    - Hysteresis: Post-starburst galaxies show asymmetric return times: SF→Q transitions are rapid (feedback-assisted), Q→SF require external inflow events; thus $P(\mathrm{PSB})$ correlates with local overdensity and minor-merger rate.

- Tests.
    - Reconstruct SFHs from spectra (prospector-like fits) and measure t_{GV} vs. (halo mass, bar strength, CGM entropy). Expect t_{GV} ↓ with bar strength at fixed mass (torques speed alignment), and t_{GV} ↑ with K_{CGM}.
    - Use time-domain surveys to count burst and post-burst fractions vs. inflow variance proxies; verify the exponential sensitivity to variance/barrier height.

Falsifiability rubric (all of §8).

1. If Σ_{SFR} slopes and orthogonal scatter do not track $(p_\star, m_\star, \sigma_{\mathrm{in}})$, the self-regulation claim fails.
2. If IMF indicators wander widely without coherent shifts in t_{dep} and dust temperature, the stability-bound picture fails.
3. If CGM phase/covering fractions don't correlate with past SFR and quenching state as predicted, the "multipliers of τ" picture fails.
4. If burst/quench statistics lack the predicted variance-sensitive asymmetries, the $\dot{D}$ geometry is wrong.

Clear passes across these tests would strongly support q→τ as the organizing grammar of stellar and galactic evolution.

9. Numerical Program

9.1 Implement $D(q \parallel \tau)$ estimators in simulations (cloud → galaxy → cosmology)

Goal. Build a runtime and post-processing toolkit that measures *mismatch* between simulated state $q$and constraints τ, producing a scalar D and term-wise residuals.

a) Define residual library (by scale).

- Cloud (pc–10s pc): virial error $\mathcal{R}_{\mathrm{vir}} = (\alpha_{\mathrm{vir}} - 1)$, force residual $\mathcal{R}_F = \nabla P + \nabla \cdot \mathbb{M} + \rho\nabla\Phi$, heating–cooling residual $\mathcal{R}_H = \Gamma - \Lambda$.
- Galaxy (kpc): mass continuity $\mathcal{R}_\rho$, vertical balance $\mathcal{R}_z = P_{\mathrm{turb}} + P_{\mathrm{th}} + P_B - W_z$, Toomre stability $\mathcal{R}_Q = (Q - 1)_-$, energy closure $\mathcal{R}_e = \dot{E}_{\mathrm{inj}} - \dot{E}_{\mathrm{diss}}$, chemo flux $\mathcal{R}_Z$.
- Cosmology (100 kpc–Mpc): CGM cooling–heating $\mathcal{R}_{\mathrm{cool}}$, boundary flux matching $\mathcal{R}_{\mathrm{bdy}}$, halo baryon fraction closure $\mathcal{R}_{f_b}$.

b) Assemble divergence.

$$D(q \parallel \tau) = \int_{\Omega} \sum_{i} w_i \frac{\mathcal{R}_i(q;\tau)^2}{\sigma_i^2} dV \text{ with } \sigma_i = \text{tolerance from transport/measurement.}$$

c) Runtime instrumentation (AMR/SPH/meshless).

- Add kernel modules to compute $\mathcal{R}_i$ per cell/particle; accumulate blockwise D and export light diagnostics.
- Produce D-maps (3D or projected), term budgets, and eigenmodes of the local Hessian H_D for stability.

d) Post-processing.

- Reduce to radial profiles (e.g., $\langle \mathcal{R}_Q^2 \rangle(R)$), phase-plane residuals (e.g., $\mathcal{R}_H$ vs. n, T), and timeline $D(t)$.
- Correlate $\dot{D}$ with observables (SFR, outflow rate, QNM-like disk modes) to verify contractivity.

e) Validation.

- Unit tests with analytic equilibria (isothermal sphere, hydrostatic slab, de Sitter core toy).
- Convergence: $\Delta D \to 0$ under resolution/refinement and subgrid toggles.

9.2 Alignment-aware subgrid models; diagnostics for radiative and kinetic feedback

Principle. Make subgrid closures *respond to misalignment* so that $\dot{D} \leq 0$ holds generically (proportional–integral control).

a) Star formation & turbulence.

- SFR per cell: $\dot{\rho}_\star = \epsilon_{\mathrm{ff}} \rho / t_{\mathrm{ff}}$ with
  $\epsilon_{\mathrm{ff}} = \epsilon_0 \, [1 + k_P \, \Delta_Q + k_E \, \Delta_E]_+$,
  $\Delta_Q = (Q_{\mathrm{targ}} - Q)$, $\Delta_E = (\dot{E}_{\mathrm{diss}} - \dot{E}_{\mathrm{inj}})$.
- Turbulent closure: eddy diffusivity $\nu_{\mathrm{eff}} = \nu_0 (1 + k_\nu \mid \mathcal{R}_Q \mid)$ to boost transport when disks are under-supported.

b) Feedback coupling (stellar/AGN).

- Momentum/energy injection gains scale with residuals:
  $p_\star/m_\star \to (p_\star/m_\star)\,[1 + k_p\,\Delta_Q + k_z\,\Delta_z]$, with $\Delta_z = W_z - (P_{\rm turb} + P_{\rm th} + P_B)$.
- AGN duty: trigger when central $\mathcal{R}_{\rm cool} > 0$(cooling excess) and integrate an *I-term* to avoid oscillations:
  $L_{\rm AGN} \propto \dot{M}_{\rm BH}[1 + k_I \int \mathcal{R}_{\rm cool}\,dt]$.

c) Radiation & chemistry.

- Radiative transfer subgrid (M1/FLD): adapt escape fractions to minimize $\mathcal{R}_H$; if $\mathcal{R}_H > 0$ persistently, increase dust IR trapping or photoelectric heating until $\partial D/\,\partial\kappa \to 0$.
- Metal mixing: set diffusivity $D_Z = D_{Z,0}(1 + k_Z\,|\,\mathcal{R}_Z\,|)$.

d) Diagnostics.

- Log controller states ($\Delta_Q, \Delta_E, \int \mathcal{R}_{\rm cool}$) each timestep to confirm contraction: $\Delta D \le 0$ in relaxation phases; flag "learning failures" where $\Delta D > 0$ persists.
- Report loss attributions: contribution of each $\mathcal{R}_i$to D(waterfall plots), and *which closure* reduced it.

e) Stability & causality checks.

- Clamp gains so that the effective operator $\mathcal{G}^{-1}H_D$ has positive eigenvalues (no flip into explosive modes).
- Ensure locality and light-speed limits for radiative/kinetic channels.

9.3 Benchmark suites: reproduce scaling relations via stationarity, not curve-fitting

Objective. Demonstrate that classic relations emerge as D-minima without hand-tuning.

a) Controlled boxes (galaxy patches).

- Suite A: stratified boxes with varying $\Sigma_{\rm g}$, $\Sigma_{\rm tot}$; measure Q, $t_{\rm dep}$, and $\Sigma_{\rm SFR}$.
  Target: linear-to-superlinear $\Sigma_{\rm SFR}$ slope transitions captured by D-stationarity; orthogonal scatter $\propto \sigma_{\rm in}$.

b) Whole-galaxy discs.

- Suite B: isolated discs with spins λ, gas fractions, and feedback knobs; run to steady state.

Targets: Toomre self-regulation ($Q \approx 1$maps), TF slope $\alpha \sim 3 - 4$ without fitting, MZR via box closure with winds.

c) Cosmological halos (zoom-ins).

- Suite C: M_{200} grid across epochs; vary CGM entropy floors.
  Targets: star-forming main sequence normalization; quenching thresholds at fixed K_{CGM}; CGM covering fractions tracking past SFR with predicted lag.

d) Time-domain tests.

- Burst–quench experiments by modulating $\dot{M}_{\mathrm{in}}$ and bar torques.
  Targets: green-valley times $t_{\mathrm{GV}} \approx 1/\lambda_{\mathrm{relax}}$, Kramers-like duty cycle scaling vs. variance.

e) Cross-code reproducibility.

- Run the same D-toolkit on AMR (RAMSES), moving-mesh (AREPO), and SPH (GIZMO) with identical initial conditions and controller gains.
  Metric: convergence of $D(t)$, stationarity conditions, and recovered slopes within error bars without re-tuning to match observations.

f) Public deliverables.

- DKit: open-source library (C++/Python) implementing residuals, gains, and diagnostics; hooks for major codes.
- Loss cards: standardized plots/tables of $\{D, \mathcal{R}_i\}$ vs. time for each run.
- Challenge set: initial conditions + acceptance criteria ("pass if TF, MZR, KS-law emerge with residuals <thresholds and $\dot{D} \leq 0$ after transients").

Success criterion. Scaling relations, quenching thresholds, and CGM correlations appear as by-products of minimizing D with physical transport/feedback—no curve-fitting to observations beyond microphysics. If they don't, adjust physics, not parameters, or the q→τ hypothesis fails the benchmark.

11. Conclusion

11.1 Stellar and galactic evolution as q→τ: many phenomena, one alignment grammar

Thesis. From collapsing clouds to quenching ellipticals, the same rule organizes baryonic structure: the realized state q evolves to reduce the divergence $D(q \parallel \tau)$ from a fixed set of constraints τ (budgets, symmetries, boundary fluxes). This alignment grammar turns diverse phenomena into corollaries of one flow.

Unifications achieved.

- Star formation: turbulence, gravity, and magnetic fields sculpt descent; ignition is the stationarity of heating–cooling; the main sequence is an attractor manifold; compact remnants are boundary attractors set by microphysics.
- Galactic regulation: the baryon cycle closes budgets; disk stability and transport are hard constraints; feedback acts as a proportional–integral controller enforcing $\dot{D} \leq 0$.
- Populations: the IMF turnover, metallicity laws, and Σ_{SFR}–Σ_{gas} slopes are not axioms but minima of Dunder realistic transport.
- Morphology & quenching: environmental and internal processes are bifurcations of the alignment flow; bars/compaction are transient complexity that later lowers D.
- Dark sector: halos and expansion supply informational curvature that bends the feasible manifold without adding ad hoc baryonic rules.
- Entropy & codes: galaxies shine to learn—export entropy to lower D; mature systems compress complexity into robust codes (gradients, sequences, planes).

Predictivity. The framework yields crisp, linked tests: universal self-regulation slopes tied to feedback yield and inflow variance; bounded IMF environment-dependence from manifold stability; CGM phase/covering fractions as Lagrange multipliers of τ; and burst–quench statistics set by the geometry of $\dot{D}$.

Program. Implement D-estimators and alignment-aware closures in simulations; demand that scaling relations emerge by stationarity, not tuning. Where predictions fail, revise physics (the τcolumns), not curves.

Moral. With q→τ as the arrow, stellar and galactic evolution become one story: systems radiate, rearrange, and occasionally bifurcate, but always along a path that makes their models truer to their constraints. Many phenomena, one alignment grammar.

Epilogue: Many Phenomena, One Alignment Grammar

If this paper has a single claim, it is that stellar and galactic evolution are instances of the same alignment flow: the realized state $q$descends the divergence $D(q \parallel \tau)$ toward the generative constraints τ. Stars ignite when heating and cooling reach stationarity; disks self-regulate when support and gravity balance; populations settle onto scaling relations where residual budgets vanish. What varied once looked like separate laws now reads as one grammar applied at many scales.

We have also made the claim falsifiable. The simplest tests do not demand new telescopes or heroic simulations—only new readouts. On the sky: measure how the Kennicutt–Schmidt slope and its scatter shift with two controls—feedback yield and inflow variance; trace the CGM's memory of star formation through covering fractions and entropy; time green-valley residency against bar strength and halo heating; watch metallicity gradients relax after bar-driven inflow. In silico: drop a D-estimator into existing runs and check that, after a disturbance, $\dot{D} < 0$during relaxation; add a one-line, alignment-aware gain to feedback and see whether disks drive themselves to $Q \approx 1$ without retuning. Each test has a binary outcome; together they give the theory teeth.

If these experiments succeed, alignment becomes a working principle rather than a metaphor. The IMF's stability, the shape and scatter of star-formation laws, the MZR and TF relations, quenching thresholds, CGM phase structure—each would appear as a minimum of Dunder transparent constraints and boundary fluxes. If they fail, we learn exactly which column of τ—a closure, a boundary condition, a feedback channel—was mis-specified. Either way, the method points to physics, not curve-fitting.

The practical payoff is a new style of modeling: diagnose first, tune last. Build residual libraries, measure D and $\dot{D}$, expose which budgets drive misalignment, then change the physics that matters. Share diagnostics—loss cards, D-maps, controller states—so results transfer across codes and surveys. In this mode, consensus emerges from common constraints, not common parameter sets.

Galaxies, like stars, shine to learn: they export entropy to lower D, grow complexity to satisfy constraints, then compress that complexity into robust codes—gradients, sequences, planes. The program ahead is to read those codes with the right loss function, and to let our models learn the same way the systems do. If the quick tests outlined here light up as predicted, we will have shown that from clouds to clusters, q→τ is not merely a unifying slogan—it is the operating system of luminous structure.

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Note: Items (1)–(2) are the two requested ResearchGate publications; the remaining entries provide a representative, standard backbone for star formation, feedback, CGM, scaling relations, and simulation frameworks that the q→τ paper engages with.

Appendix: Simplest Experiments

A) Re-analyze existing observations (no new hardware)

1. Self-regulation slope & scatter test (KS law with controls)
    - Do: For IFU/ALMA samples (kpc patches), regress $\Sigma_{\rm SFR}$on $\Sigma_{\rm gas}$ with two covariates: feedback yield proxy $(p_\star/m_\star)$(use wind momentum per SFR, or SN rate × typical momentum) and inflow variance proxy (H I asymmetry/warps, satellite counts, or kinematic lopsidedness).
    - Prediction: Slope $N \approx 1$ when $\left(\frac{p_\star}{m_\star}\right)$ is high; $N > 1$in compact starbursts. Orthogonal scatter $\sigma_\perp \propto \sigma_{\rm in}/(1+\eta)$.
    - Falsifier: No trend of Nor $\sigma_\perp$ with these controls.
2. IMF stability bounds via "tri-variation"
    - Do: At fixed $\Sigma_{\rm gas}$ and Z, compare IMF indicators (e.g., Na I, CaT or dynamical M/L) against (i) depletion time $t_{\rm dep}$ and (ii) dust temperature (a proxy for radiation field).
    - Prediction: If IMF shifts (top-heavier), then coherently: $t_{\rm dep}$ ↓and dust T ↑. Magnitudes bounded ($|\Delta m_c/m_c| \lesssim$ ~0.3) outside extreme environments.
    - Falsifier: Large IMF swings without the paired shifts in $t_{\rm dep}$ and dust T.
3. CGM "Lagrange multipliers" (memory & entropy)
    - Do: Cross-match CGM covering fractions (H I/OVI) with galaxies' past SFR averaged over 1–2 Gyr (from SFH fits), plus a CGM entropy proxy (X-ray K, where available).
    - Prediction: $f_{\rm cov}$ correlates with time-averaged SFR (fountain memory), anticorrelates with instantaneous η at fixed mass; quenched systems show high $K_{\rm CGM}$, low $f_{\rm cov}$, long re-accretion times.
    - Falsifier: No lagged correlation; CGM phases unrelated to SFR/quenching state.
4. Green-valley residence times vs. bar strength & CGM entropy
    - Do: Measure $t_{\rm GV}$ (from SFHs) versus bar strength and $K_{\rm CGM}$ (or group/cluster membership).

- Prediction: $t_{\mathrm{GV}} \downarrow$ with stronger bars (faster torque-driven relaxation), $t_{\mathrm{GV}} \uparrow$ with higher K_{CGM} (harder to re-fuel).
- Falsifier: Flat or opposite trends.

5. Metallicity-gradient relaxation after bar-driven inflow
   - Do: In barred galaxies with known inflow episodes, track $Z(R)$ profiles across time bins (or compare barred vs unbarred twins).
   - Prediction: Temporary gradient flattening/inversion followed by diffusive recovery with timescale $\tau_{\mathrm{mix}} \sim R^2/D_Z$.
   - Falsifier: No relaxation pattern; gradients uncorrelated with bar history.

B) Minimal simulation toggles (hours–days, not months)

6. Drop-in D-estimator in any existing run
   - Do: Compute a simple $D = \int [(Q - 1)_-^2/\sigma_Q^2 + (\dot{E}_{\mathrm{inj}} - \dot{E}_{\mathrm{diss}})^2/\sigma_E^2 + \mathcal{R}_H^2/\sigma_H^2]\, dV$ each snapshot for one disk simulation.
   - Prediction: After perturbations (inflow pulse, merger), $\dot{D} < 0$ during relaxation back to the star-forming main sequence.
   - Falsifier: Persistent $\dot{D} > 0$ or no decay of D despite apparent "equilibrium".
7. Alignment-aware feedback micro-controller
   - Do: Modulate SN/stellar momentum coupling by residuals, e.g. $p_\star/m_\star \leftarrow (p_\star/m_\star)[1 + k_P(Q_{\mathrm{targ}} - Q)]_+$. Leave everything else unchanged.
   - Prediction: System self-drives to $Q \approx 1$, reproduces KS slope and t_{dep} without retuning; orthogonal scatter scales with imposed inflow variance.
   - Falsifier: Requires ad-hoc tuning to recover basic laws; no contraction in D.
8. Bar/compaction impulse test
   - Do: In a stable disk, briefly impose a bar-like torque or central inflow; then remove it and follow recovery.
   - Prediction: Short-term rise in complexity (non-axisymmetry), then lower final D (stabilized outer disk, adjusted central support), plus predicted metallicity/age signatures.

- Falsifier: No net Dreduction or contradictory chemo-dynamical footprints.

C) Single-galaxy "control-volume" experiment (one object, many maps)

9. D-map for a nearby grand-design spiral
    - Do: Combine H I+CO (gas), IFU (SFR, kinematics, Z), and stellar mass maps to build per-pixel residuals: $(Q-1)^2_{-}$, vertical pressure mismatch, and heating–cooling residual.
    - Prediction: Star-forming arms sit near D-minima; recent-merger or warp regions show high Dthat decays along the flow time toward the bar/inner ring.
    - Falsifier: No spatial structure in D; high-D regions don't relax despite ample time.

Why these are "simplest"

- They re-use existing surveys (ALMA, MaNGA/SAMI, COS-Halos, HST/JWST SFHs) and existing simulations, adding only new regressors or a lightweight D calculator.
- Each has a binary falsifier: a specific correlation or $\dot{D} < 0$ behavior that must appear if q→τ is the right grammar.

One-page cheat outcomes

- Pass signals: $N \to 1$with high feedback yield; KS scatter tracks inflow variance; CGM memory of past SFR; t_{GV}vs. bars/entropy; gradient relaxation; $\dot{D} < 0$ after disturbances.
- Fail signals: No dependence on the stated controls; IMF swings unpaired with t_{dep}/dust T; CGM phases unrelated to history; D doesn't contract.

Do 2–3 of these first (A1, A3, B6). If they light up as predicted, the theory earns serious credibility fast—and sets the stage for the fuller numerical program.